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The Effects of Tool Degradation on Hole Straightness in Deep Hole Gundrilling of Inconel-718

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Abstract

Straightness control in deep hole gundrilling of Inconel-718 is challenging. In this study, the drills are found to degrade rapidly on the cutting edges, bearing pads and side margins, largely due to the extreme heat resistivity of the high temperature superalloys. Severe adhesive wear developed on the rake and flank faces deteriorates cutting efficiencies of the cutting edges while diffusive wear on the bearing pads and side margins deteriorates self-piloting efficacies of the drill. Coupled with highly irregular wear rates on the inner and outer cutting edges, the drills are forced against the hole at high rotational speeds – leading to escalations in frictional contact, heating and thermal damage on the bearing pads and side margins. As a consequence, the drills are deflected from the designated drilling course and resulted in straightness deviation on the part of hole drilled. Through the accumulation of partial straightness deviation over the course of high aspect ratio drilling, the final hole produced is deflected in a constant trend as governed by the rate and behaviour of tool degradation.

Keywords: Deep hole drilling; Tool wear; Hole straightness

1. Introduction

Gundrilling is a specialized drilling process to construct deep holes with typical diameters between 3 to 25mm and depth to diameter ratios of greater than 10. Although it was first invented approximately a century ago for the production of solid gun barrels [1], the use of gundrilling can now be found in many modern industrial applications. One important example involves the drilling of wire-line, flow-line and port holes on advanced downhole equipment for drilling and evaluation, mainly used in oil & gas exploration. Such downhole equipment are made of corrosion resistant alloys like Inconel-718, specially engineered to operate autonomously under high pressure, high temperature and highly corrosive conditions.

But Inconel-718 is extremely difficult to machine. This is largely due to its extreme work hardenability [2] and thermal resistivity [3], especially for the special grades used in this application that requires very high yield strength (minimum 1034MPa). Through sub-surface deformation during initial cutting on the surface, hardness of the sub-surface layer increases correspondingly to continuous chip formation. Thus, greater amount of force is required to remove the same amount of materials in the subsequent cycle of chip formation. As a result, drills degrade rapidly during the process. More detrimentally, significant heat is generated on cutting edges and bearing pads of the drills through continuous cutting and self-piloting respectively. But a large fraction of the heat is taken by the drills, as the thermal conductivity of Inconel-718 is very much lower than that of the carbide drill tip [4], often in the region of 4-5 times. Therefore, gun drills are found to fail through thermal-mechanical damage, unlike the drilling on conventional materials like aluminum alloys, cast irons and alloyed steels.

Subjected to a continuous off-center, asymmetrical and single flute cutting in gundrilling, deep holes produced in this application deviates in a constant trend. Yet, despite the significance of complex loading and tool degradation conditions described above, little is known about the effects

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of tool degradation behavior on the resultant hole straightness. The attempt to reveal this relationship, both qualitative and quantitative through actual deep hole drilling experiments and analysis became the main objective of this study. The experimental study was conducted on a uniaxial deep hole gundrilling machine. The scope was limited to a drilling aspect ratio of 125 (8mm in diameter and 1000mm in depth). The chips generated were collected to estimate the rate of tool degradation and deterioration in cutting efficiency. Vibration was acquired with Kitsler accelerometer and customized instruments. Wear mode of the drills was characterized with scanning electron microscopy and energy dispersive X-ray spectroscopy. In addition, hole finishing and straightness were evaluated with video borescope and ultrasonic gauges. The experimental findings and analyses indicate that hole straightness is governed by degradation of the gun drills.

Nomenclature

d	Drill diameter
E_s	Young's modulus of drill stem
E_w	Young's modulus of workpiece
e_c	Eccentricity of thrust force
I	Area moment of inertia of gun drill stem
L	Length of the drill
l_n	Length of drilled hole
P	Thrust force acting on gun drill
y	Deflection of gun drill stem
y_n	Drill tip deflection at distance l_n
σ_y	Yield strength of workpiece
α	Springback magnitude
ε_p	Equivalent plastic strain
V_f	Relative surface speed
F_n	Compressive force
F_f	Frictional force
μ	Coefficient of friction
η	Fraction of heat generation
Q	Heat flux
V	Volumetric loss through adhesion
$K_{adhesion}$	Adhesive wear constant
a	Hardness constant
T	Interfacial temperature
w	Width of cut
σ	Average normal force
σ_y	Yield strength of material
α	Springback intensity
θ_o	Initial drill tip inclination
θ	Initial drill tip inclination at any given length (l)
Δt	Time interval

Table 1. Chemical compositions and mechanical properties of Inconel-718.

Chemical Composition				
Ni + Co	Cr	Fe	NB + Ti	Mo
54.50%	18.60%	17.10%	5.10%	3.00%
Mechanical Properties				
Yield Strength	Tensile Strength	Hardness	Elongation	Red. of Area
1165MPa	1232MPa	38-40HRc	29.70%	45.90%

2. Experimental Setup

Experimental test drilling was set off to drill two blind holes on a 2.0-m cylindrical Inconel-718 workpiece. Major chemical compositions and mechanical properties of the workpiece are summarized in Table 1.

Gun drills with single flute, TiAlN-coated K-type carbide tips in three different lengths ranging from 1000mm to 2000mm were used progressively for the drilling. The drills had uniform slash-type design with equal approach angles of 15° on the cutting edges. The relief angles were 15° and 20° for the inner and outer cutting edge respectively. The upper bearing pad was located at approximately 75° from the margin and covered 106° of the bottom of the drill for 'Form C' configuration. The lead-in chamfer was 45°. In addition, the drills have two coolant channels for the supply of coolant to the cutting point and then circulated back to the system through the 120° V-groove across the rake face.

The cylindrical workpiece was supported with a pair of heavy duty V-blocks and securely clamped on to the bed of the gundrilling machine as shown in Fig. 1 (a, b). The rotational speeds and feed rates of the drills were kept between 600 to 800rpm and 5 to 8mm/min respectively. Coolant pressure and chiller temperature were consistently maintained at 70 bar and 25°C respectively. Each set of new gun drill was subjected to a fixed drilling cycle of 50mm. With the tool degradation developed, the drills would then be subjected to manual resharpening as described in [5]. The two holes constructed are shown in Fig. 1(c).

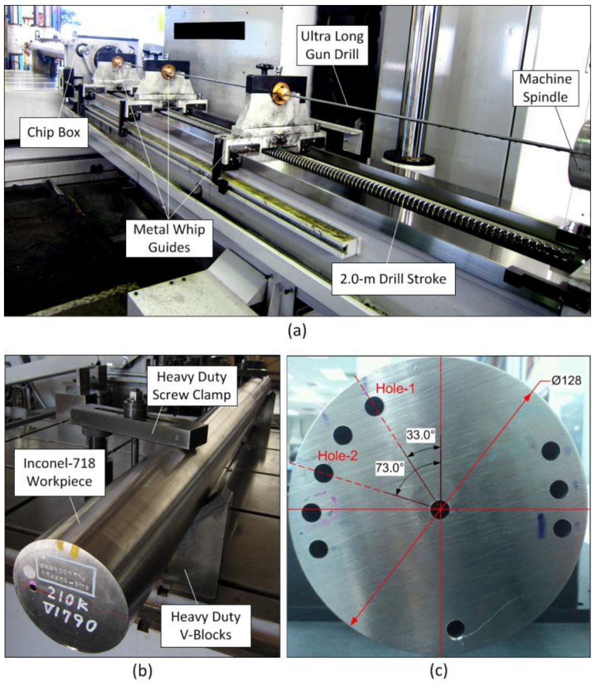

Fig. 1. (a) Experimental setup; (b) Mounting of 2.0-m Inconel-718 workpiece; (c) Two holes, Hole-1 and Hole-2 being drilled.

3. Results and Discussion

Inconel-718 is difficult to drill mainly due to its work hardenability and heat resistivity. In conjunction with the exceptionally high yield strength workpiece used in this study, drill degradation took multiple forms on the cutting edges, bearing pads and side margins. This is largely governed by the thermal-mechanical loading on the interacting surfaces.

3.1. Steady Tool Wear

Tool wear was developed on different parts of the carbide drill tips during a drilling cycle is shown in Fig. 2: (a) upper and (b) lower bearing pads; (c) inner and (d) outer flank faces; (e) side margin; and (f) inner and (g) outer rake faces.

Wear around the cutting edges was formed by erosion during cutting while wear on the bearing pads was caused mainly by the built-up edges. The built-up edges arise mainly from the welding of the workpiece material onto the cutting edges due to extreme temperature generated from the rubbing and whipping actions of the drill.

Once the size of the chip becomes mature, it flows continuously on the rake faces of both inner and outer cutting edges at different rates. The rate of chip flow changes according to the function of cutting speed reduction from the outer diameter to the center of the drill. The flow of chip generates continuous mechanical abrasion to the rake faces due to the highly abrasive particles in Inconel-718 and this leads to the increase in local temperature on the rake faces through frictional heating. Most of the heat flux is conducted into the carbide instead of carried away by the chip. As a result, crater wear is developed on the rake faces.

Moreover, tool wear on the flank faces of the cutting edges is developed simultaneously following constant adherence with the bottom of the hole. This could largely be due to springback or elastic recovery of the tough Inconel material after a cut is made, despite the incorporation of relief angles. But further increase of the magnitude of relief angles may not be feasible to maintain the strength of the cutting edges. Thus, wear development on the flank faces of both inner and outer cutting edges is inevitable.

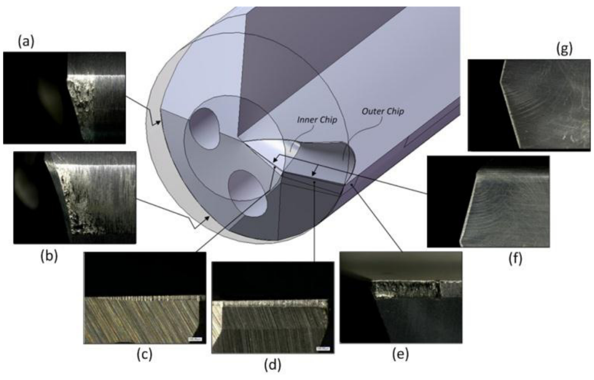

Fig. 2. Wear regions on gun drills after deep hole drilling of Inconel-718.

As gundrilling is an asymmetric and off-center drilling operation, the thrust and cutting force components deflect the drill tip towards the wall of the hole continuously in the radial direction. The deflecting mechanism is counterbalanced by the primary bearing pads located in the opposite of the cutting edges and supported by the side margin of tip as the configuration of the bearing pads is designed to incorporate a support system on the drill tip for self-guiding purposes. Thus, the bearing pads are subjected to the resultant force of the cutting and thrust components in the direct opposite direction when the drill tip is forced against the hole and lead to severe frictional contact in conjunction to continuous rotation of the drill. As a consequence, significant adhesive and abrasive wear are developed on the bearing pads and side margin.

Concurrent tool wear development on the rake and flank faces changes the drill geometries and deteriorates the quality of cutting edges. The chip formation and chip breaking capabilities of the gun drill are thus adversely affected. On the other hand, wear on the bearing pads and side margin introduces random variability to the outer diameter profile of the drill which reduces its self-guiding and self-support capabilities. Failure in controlling wear around cutting edges leads to the production of long and thick chips that could not be easily broken and evacuated through the use of high pressure coolant while failure in controlling wear on the bearing pads increases the magnitude of drill whipping during the process when the drill tip could not support the entire drill effectively. Combining both phenomena deteriorate the overall process stability and induce damages to the drill.

3.2. Thermal-Mechanical Damage

3.2.1 Rake Face

During the cutting process, the rake face is continuously covered by the newly formed chip and this prevents the coolant from reaching the rake faces. Although heat can be partially carried away by the chip and coolant through convection, the amount involved is negligible due to poor thermal conductivity of Inconel-718 comparing to carbide.

The rake face is initially abraded mechanically by the flowing chip. The chip itself contains abrasive particles that further causes abrasive wear along the tool-chip contact length. Significant amount of heat is generated through frictional sliding of continuous chip flow as well as plastic deformation during chip formation. Most of the heat generated will be transferred to the rake face since the cemented carbide material has a higher thermal conductivity when compared with Inconel-718. The temperature on the rake face is theoretically estimated to range between 600°C and 700°C in some extreme cases depending on the chip flow rate. In addition, the flow of the chip further creates high compressive pressure on the rake face when it makes contact with the tool. Under such a high temperature and pressure condition, bonding between the tool and chip takes place. This leads to the formation of built-up edges through cold welding process or adhesion.

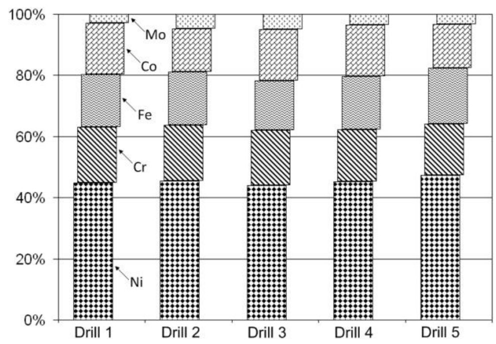

Fig. 3. Elemental analysis on the rake faces of five gun drills.

In order to verify the characteristics of cold-welding material on the rake face, all carbide drill tips (5 out of 6 were removed from the drill stems) were subjected to a series of elemental analyses with energy-dispersive x-ray spectroscopy (EDS). Five major elements of Inconel materials were investigated namely nickel (Ni), chromium (Cr), iron (Fe), cobalt (Co) and molybdenum (Mo). Significant level of Ni, Cr and Fe can be identified on all the rake faces as shown in Fig. 3. These evidences indicate adhesive wear on the rake face due to the cyclical built-up and peeling of the welded Inconel materials from the cutting edges.

3.2.2 Flank Face

Based on the current cooling channel design, the coolant should in theory reach the cutting edges with conventional materials like steels. In this study, it is almost impossible for coolant to reach the flank faces due to springback of the newly generated surfaces. This prevents the tool to cleanly shear the chips from the workpiece thereby leaving uncut material for the next cutting cycle while at the same time lead to notching, as shown in Fig. 4. Thus, if the rake face is not receiving sufficient lubrication, the flank face will naturally be subjected to heavy abrasive and adhesive wear. The formation of notching is described as follows.

Refer to Fig. 5, the springback intensity is governed by the yield strength of the work material. When the yield strength σ_y is high, 1165 MPa in this case, the magnitude of springback α increases correspondingly:

$$\alpha = \frac{\sigma_y \cdot \varepsilon_p}{E_w} \tag{1}$$

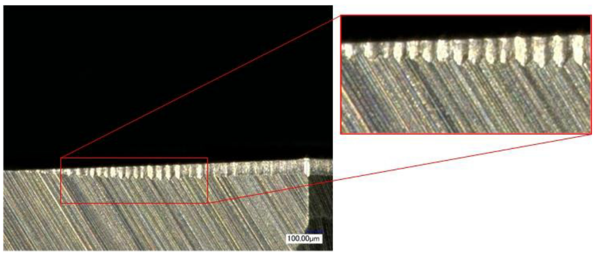

Fig. 4. Notch damage on flank face.

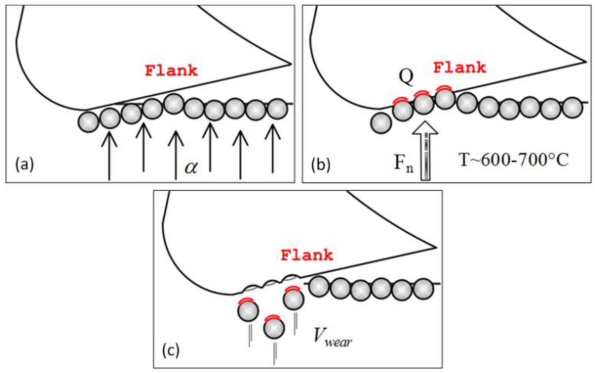

Fig. 5. Formation of notch damage subsequent to adhesive wear. (a) Springback of machined surface with an average magnitude α; (b) Localized temperature rise through frictional heating, leading to the formation of built-up edge; (c) Collapse of built-up edge that forms notches.

Although V_f on the flank face is not as high as the rake face, the high F_n at the localized tool-work interface could lead to severe frictional sliding and thus F_f. The frictional forces generate extreme heat, Q through rubbing and plowing actions on the flank face.

$$F_f = \mu \cdot F_n \tag{2}$$

$$Q = \eta \cdot F_f \cdot V_f \tag{3}$$

With the heat resisting behavior of Inconel-718, majority of heat flux is transferred to the drill through conduction, leading to extreme temperature. Bonding between the tool and work is generated when the flank face adheres to the bottom of the hole under intense temperature and pressure. This in turn will produce random built-up edges along the flank face. Localized seizure usually takes place momentarily at the affected zones. This seizure causes the built-up edges to peel, which in turn will detach tool materials from the flank face, resulted in a volumetric loss of work material [6]:

$$V = K_{adhesion} \cdot e^{aT} \cdot V_f \cdot w \cdot \sigma \cdot \Delta t \tag{4}$$

The other major causes of premature tool failure could partially be due to the inclusion of abrasive and hard particles within the work piece material but notch damage is particularly apparent in this study where Inconel-718 material with very high yield strength was the subject of interest. To establish the characteristics of adhesive wear, the flank faces were further analysed with EDS. As shown in Fig. 6, the high percentages of Ni, Cr and Fe on the flank faces clearly indicate the cold welding of Inconel materials.

3.2.2 Bearing Pads & Side Margins

Bearing pads and side margins are designed to support and guide the gun drill using the preceding hole as an indirect bush. But the gap between the preceding hole and the bearing pads/side margin leaves very little clearance for the coolant to provide the critical cooling and lubrication functions. Coupled with high contact loading, extensive wear and cold-weld damages were observed on all the tools used. The wear and built up edges on the pads and margins in turn causes the drill to lose its geometrical integrity and self-guiding capability.

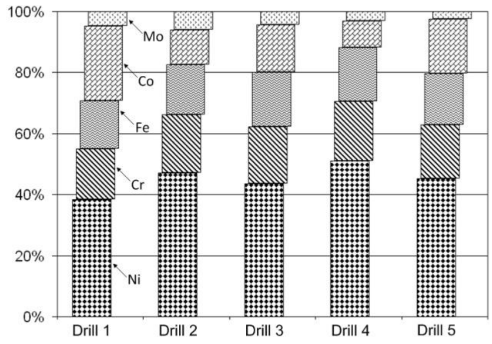

Fig. 6. Elemental analysis on the flank faces of five gun drills.

Wear behavior on the bearing pads and side margin is complex. It combines the extreme heat generated from frictional sliding alongside random shearing and plowing arising from the process; as well as other dynamic effects such as whipping, whirling and chattering. Since the gun drill has a single flute that provides asymmetrical cutting action, the drill is often forced against the sides of the hole in order to counterbalance the major force components generated from chip formation. Tight contacts between the hole and drill generate high compressive pressure on the bearing pads and side margin. Severity of frictional heating deepens, leading to an aggressive increase in surface temperatures that promotes formation of built-up edges through adhesion.

High interfacial temperatures between the hole and the side margin together with the lack of sufficient cooling and lubrication, create an ideal condition for both adhesion and diffusion. Since thermal conductivity of cemented carbide is significantly higher than Inconel-718, there is a higher tendency for Inconel particles to be bonded onto the carbide edges. While within the cemented carbide matrix, cobalt particles are thermally more active than tungsten carbide particles, making it more susceptible to diffuse externally from the side margin and bearing pads. As cobalt is the binding agent, the loss of cobalt particles through diffusion dislodge hard and brittle tungsten carbide grains from the matrix and resulted in severe volumetric loss on the affected zones, as shown in Fig. 7.

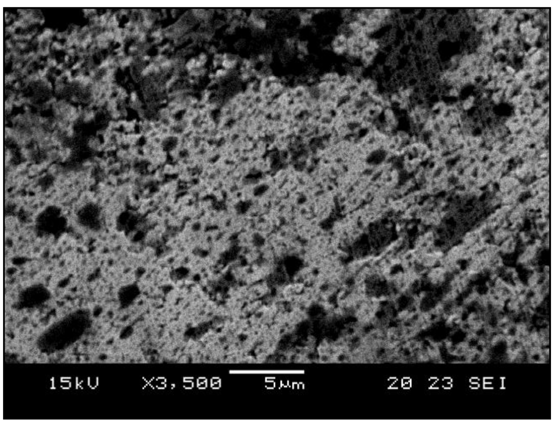

Fig. 7. A sample of bearing surface with the loss of cobalt through diffusion.

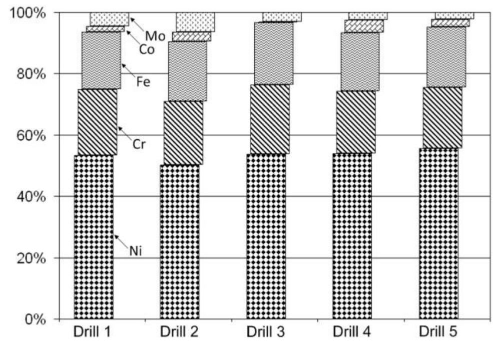

Fig. 8. Elemental analysis on the bearing pads of five gun drills.

Another series of EDS analyses were conducted on the bearing pads of the drills to examine the conditions of adhesion and diffusion. Fig. 8 summarizes the elements detected on the bearing pads. The analyses show an unusually low percentage of cobalt on the bearing pads when compared to that of the rake faces (see Fig. 3) and the flank faces (Fig. 6). This indicates that the rake and flank faces are relatively hotter when compared with the side margin and bearing support pads. According to theoretical estimations, surface temperatures of the bearing pads and side margins could exceed 1000°C when cobalt particles are dislodged from the tungsten carbide matrix.

3.3. Hole Straightness Analysis

The Inconel workpiece, gun drill, drill bush and whip guides were properly aligned against the drilling axis in order to eliminate the effect of support misalignment. After each cycle of drilling, straightness of the hole was measured with ultrasonic gauges according to EN 15317. Straightness deviations of Hole-1 and -2 are plotted in Fig. 9.

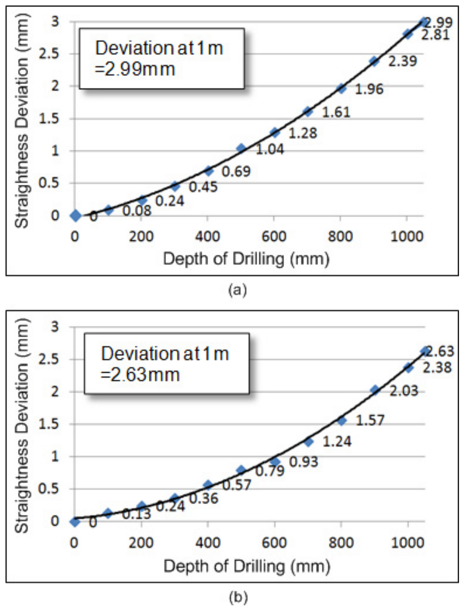

Fig. 9. Hole straightness profile. (a) Hole-1 and; (b) Hole-2.

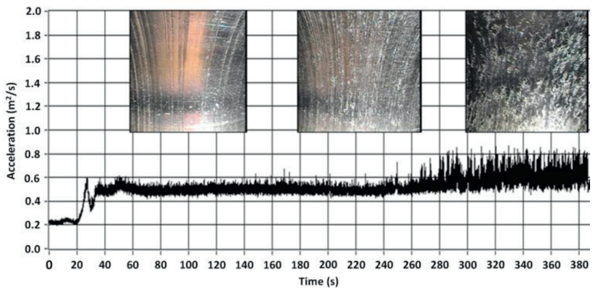

Fig. 10. Deterioration in vibration and hole finishing.

With the presence of long chips, the drills are insufficiently cooled and lubricated on the cutting edges and bearing pads on the peripheral respectively. Wear on the rake and flank faces develops rapidly, which leads to a reduction in cutting efficiency and process stability. Coupled with excessive thermal damage on the bearing pads and side margins, the drills are forced against the wall of the hole, resulted in greater frictional contact that impairs the hole finishing, as shown in Fig. 10. Under such loading condition, the drill is deflected from the designated drilling course, associated with the shift of thrust force eccentricity towards the outer cutting edge as shown in Fig. 11. Wear on outer cutting edges is more rapidly developed than the inner counterpart due to the higher cutting speeds involved. To understand the mechanism involved, the drills can idealized as column structures with one end fixed and the other end pinned. The initial inclination of the drill tip θ_o due to tool degradation induced after the initial drilling cycle can be shown in Fig. 12. According to [7], deflection of the drill stem due to the inclination of drill tip is given by:

$$y = -e_c\left[\tan\left(\frac{kL}{2}\right) sin(kl) + cos(kl) - 1\right] and\ k = \sqrt{\frac{P}{E_S I}} \quad (5)$$

With the shift and increase in thrust force eccentricity, the deflection of the steam increases correspondingly with tool degradation. The inclination θ at a given length, l is the slope of the defection profile at that point:

$$\theta = \frac{dy}{dl} = -e_c\left[\tan\left(\frac{kL}{2}\right) cos(kl) + sin(kl)\right] \quad (6)$$

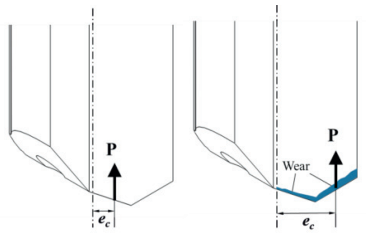

Fig. 11. Shift in eccentricity of thrust force driven by tool wear.

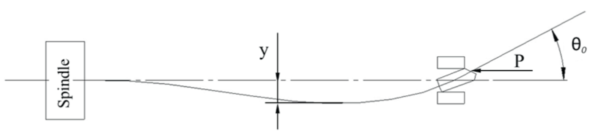

Fig. 12. Inclination at the end of first drilling cycle.

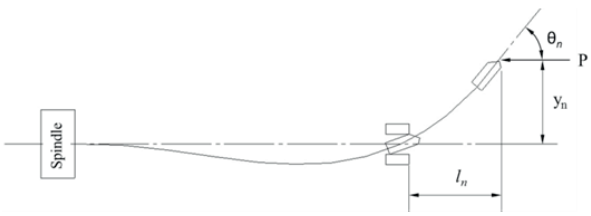

Fig. 13. Inclination at the subsequent drilling cycle after drilling depth l_n.

Subsequent deflection of the drill tip after further penetration of *dl* will become as shown in Fig. 13:

$$y_1 = y_0 + \theta_0 \times dl \quad (7)$$

Thus, drill tip deviation y_n at any given length l_n can be obtained with an iterative method described in [8]. These expressions account for the shift in thrust eccentricity due to tool degradation and provide a description for hole deviation.

4. Summary

In this paper, tool degradation is found to have significant effects on hole straightness in gundrilling of Inconel-718. Based on the experimental findings and analyses, the following conclusions are drawn:

- Thermal damage on gun drills is significant due to heat resistivity of Inconel materials
- Process stability and hole finishing deteriorate with the development of tool degradation
- Degradation on inner and outer cutting edges is not uniform owing to cutting speed variation
- Hole straightness is governed by tool degradation due to changes in thrust force distribution on cutting edges

Accurate prediction of hole straightness will only be feasible with detailed modelling of chip removal, depth-dependent cutting forces, reaction forces on bearing pads and torsional vibration behaviour of the long and slender drills.

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